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90-0033

IZF 1990 B-5

THE EFFECT OF CONDENSATION IN CLOTHING ON HEAT TRANSFER

W.A. Lotens
F.J.G. van de Linde
G. Havenith

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TNO-report

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Number of pages: 40

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Report No.:	IZF 1990 B-5
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Institute:	TNO Institute for Perception
Date:	April 1990
HDO Assignment No.:	B87-63
No. in Program of Work:	736.1

SUMMARY

A condensation theory is presented, that enables the calculation of the rate of vapour transfer with its associated effects on temperature and total heat transfer, inside a clothing ensemble consisting of underclothing, enclosed air, and outer garment. The model is experimentally tested by three experiments: 1 impermeable garments worn by subjects with and without plastic foil around the skin, blocking sweat evaporation underneath the clothing; 2 comparison of heat loss in impermeable and semipermeable garments and the associated discomfort and strain; 3. subjects working in impermeable garments in cool and warm environments at two work rates, with and without external radiation, until tolerance.

The measured heat exchange and temperatures are calculated with satisfying accuracy by the model (mean error = 11, sd = 10 W/m^2 for heat flows and .3 and .9 °C for temperatures, respectively). A numerical analysis shows that for total heat loss the major determinants are vapour permeability of the outer garment, skin vapour concentration, air temperature and clothing insulation. In the cold the condensation mechanism may completely compensate for the lack of permeability of the clothing as far as heat dissipation is concerned, but in the heat impermeable clothing is more stressful.

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Het effect van condensatie in kleding op warmte afgifte en warmte belastheid

W.A. Lotens, F.J.G. van de Linde en G. Havenith

SAMENVATTING

Een condensatietheorie waarin kleding wordt voorgesteld door onderkleding, een ingesloten luchtlaag, en buitenkleding, maakt het mogelijk warmte afgifte en temperaturen in de kleding te berekenen. Dit kledingmodel is experimenteel getoetst aan drie experimenten: 1. met impermeabele kleding die door proefpersonen gedragen wordt, terwijl de zweetverdamping onder de kleding al of niet geblokkeerd wordt met plastic folie; 2. vergelijking van warmteverlies en discomfort in semipermeabele en impermeabele kleding; 3. met proefpersonen die in impermeabele kleding werken bij een koele en een warme omgeving, bij twee arbeidsniveaus en al of niet met zon, tot de tolerantiegrens is bereikt.

De experimenteel bepaalde warmtestromen en temperaturen komen goed overeen met de modelberekeningen (fout = 11, sd = 10 W/m^2 voor warmtestromen en .3 resp. .9 °C voor temperaturen). Een numerieke analyse laat zien dat permeabiliteit, waterdampconcentratie aan de huid, luchttemperatuur en kledingisolatie de belangrijkste variabelen zijn voor de totale warmteafgifte. In de kou kan het condensatiemechanisme het gebrek aan waterdampdoorlaatbaarheid volledig goed maken voor wat betreft de warmteafgifte, maar in de warmte is impermeabele kleding belastender.

1 INTRODUCTION

Condensation of evaporated sweat inside clothing is a highly relevant factor in comfort, strain and clothing design. In comfortable conditions, condensation is not likely to occur, since the evaporation rate is low. However, during work significant quantities of sweat will be produced, that may or may not evaporate and dissipate through the clothing, depending on the clothing properties and environmental conditions. During moderate sweating, the vapour concentration at the skin will increase to produce a vapour flow, carrying the heat of evaporation away from the skin, through the clothing or clothing ensemble. When the vapour concentration does not exceed the saturation vapour concentration, the vapour will be passed to the environment. In that case there is cooling and the clothing stays dry. Both the gradient of the vapour concentration and the temperature gradient are involved, since the temperature determines the saturation concentration.

During harder work, the vapour concentration may increase so much that somewhere in the clothing system saturation is reached. Condensation will take place there, liberating at that point the heat of condensation that had previously been taken up from the skin by evaporation. This has its impact on the temperature of the clothing, because heat production forces the local temperature to increase, thereby changing the gradient over the garment: the temperature gradient from the skin to the condensation spot will decrease, while the gradient between that spot and the environment will increase. This process may change the exact location of the condensation, but generally condensation will take place where the permeability of the clothing drops: at the inner face of a fabric layer.

At first sight the sweating may seem thermally ineffective, since the sweat and the evaporative heat did not leave the clothing. But a closer look learns that the heat has already passed a good deal of the clothing and that is a significant contribution to heat dissipation.

However, the moisture is trapped in the clothing, accumulating there. Thus during condensation there is cooling, but the clothing will become wet.

Not only lack of permeability of the clothing may cause condensation, but low air temperatures as well. In arctic clothing sweat is not likely to escape to the environment, since it will condensate and next freeze somewhere inside the clothing system. In this paper a simple physical condensation theory will be described. The theory is checked by several experiments.

Not only condensation, but also absorption and ventilation have an impact on clothing heat transfer. The effect of ventilation will be addressed here, but the effects of absorption have been treated in another paper (Lotens and Havenith, 1989a).

2 CONDENSATION THEORY

It is well possible to define a physically exact description of combined heat and moisture transfer, based on the heat and moisture conservation laws. By means of a computer program, the exact solution of these equations may be approximated by calculating the process for small increments in place and time (Farnworth, 1986).
However, this still is a quite complicated procedure, that might reveal fine details in the time pattern of vapour and temperature gradients, but is probably unnecessary for the purpose of calculating steady states. Therefore, a more simple model will be described, that includes the important features, but is easy to handle and allows an experimental evaluation.
The most relevant parameters in the model are the heat and vapour conductivity of the clothing ensemble. It mostly needs two layers, of which the outer layer has a relatively low permeability for water vapour, to get condensation. There will generally be a trapped air layer between the two clothing layers. Although not strictly necessary, it is convenient to include the outer air layer as a separate layer, since variations in air motion will affect this layer. The total ensemble comprises thus of four distinct layers. The trapped air layer may be ventilated due to motion or wind. In Fig. 1 this ensemble is schematically shown, together with the pertaining heat and water vapour resistance networks.
The networks include the resistances of the clothing layers, radiation transfer and convection. At the inside of the outer layer condensation is a drain of water vapour and at the same time a source of heat of condensation. The networks are the basis for a number of equations. At any branching point the total of heat and vapour flows should be zero.

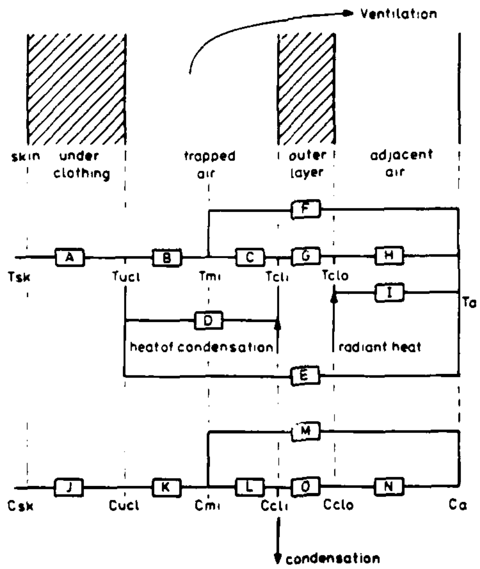

Fig. 1 The four layer clothing ensemble, together with the resistance networks for the heat and vapour transfer. D, E, and I represent radiation transfer, F and M represent ventilation, and the other resistances convective transfer.

Over parallel chains the gradient should be equal. Thus a total of 14 equations with 15 unknown variables results. These variables are the heat and vapour flows through the various layers of the ensemble, and the rate of condensation. In case of condensation the missing equation is provided by the fact that the (saturated) vapour concentration at the inside of the outer clothing layer is defined by the temperature. If there is no condensation there is one unknown variable less. In particular at the inside of the outer clothing layer holds:

$$\frac{Tmi - Tcli}{C} + \frac{Tucl - Tcli}{D} + He\ RCo = \frac{Tcli - Tclo}{G}$$

and

$$\mathbb{D}\left(\frac{Cmi - Ccli}{L}\right) = RCo + \mathbb{D}\left(\frac{Ccli - Cclo}{O}\right)$$

where He = heat of condensation (2430 J/g)

C,D,G = heat resistances (m^2K/W)

L,O - vapour resistances (m)

RCo - rate of condensation (g/m^2s)

$\mathbb{D}$ - diffusion coefficient (25.10^{-6} m^2/s)

T - temperature (K)

C - vapour concentration (g/m^3)

cl refers to outer clothing, cli for inside, clo for outside, mi refers to micro climate, ucl to underclothing.

The vapour resistance is expressed here as equivalent air layer thickness (Whelan et al., 1955). The solution of the equations is explained in the appendix. The whole procedure has been programmed in Fortran (ConRad V1.1) and requires the specification of the clothing in terms of:

- underclothing heat transfer coefficient
- trapped air thickness
- clothing surface area factor
- outer clothing heat transfer coefficient and vapour resistance
- ventilation
- external air motion
- boundary conditions such as Tsk, Ta, Csk, and Ca where sk refers to skin and a to air.

The other parameters are estimated by the program with sufficient accuracy and it takes into account geometrical factors such as the increased surface area of layers. The program calculates the wet and dry heat flows through the ensemble, the resulting temperatures and vapour concentrations, and the moisture accumulation.

A typical result is shown in Fig. 2 for a semipermeable garment, worn over cotton fatigues in a 14°C, 90% relative humidity environment, while the skin is 90% wet.

The calculation shows that under these circumstances there is considerable condensation (100 g/m^2h) despite the (moderate) permeability of the outer garment (dcl = 32 mm). This condensation takes place since the temperature and dewpoint coincide at the inner face of the outer garment. At that spot the evaporative heat flow drops and the dry heat flow increases, resulting in a constant total heat flow throughout the ensemble.

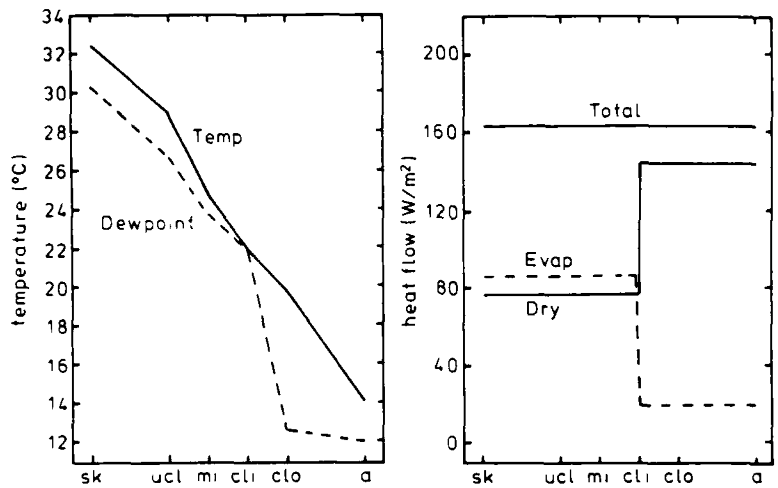

Fig. 2 Calculated temperature and dewpoint gradients, showing condensation at the inside of the outer garment (left panel). This causes a turnover from evaporative in dry heat loss, without affecting the total heat flow (right panel).

For better permeable garments there will still be condensation, until dcl is less than 2 mm, which is the vapour resistance that may actually be expected for a non-finished fabric or for the very best semipermeable fabrics. The model calculates the increase in surface temperature due to heat of condensation, the associated change in heat flow, and the condensation rate. Fig. 3 shows for a range of vapour resistances of the outer garment the gradients in the ensemble and the heat flows.

The model predicts a steep increase of Tcli with increasing condensation, pushing the other temperatures in the ensemble up. The gradient over the adjacent air layer may increase as much as 70%, increasing the dry heat flow from the garment to the air from 95 to 150 W/m^2, whereas the dry heat flow from the skin to the garment decreases.

For the evaporative term the opposite occurs. Both changes compensate each other partly, but the net effect is still that the total heat loss decreases from 210 to 155 W/m^2, comparing a permeable with an impermeable garment. For other ensembles or other boundary conditions the magnitude may be different.

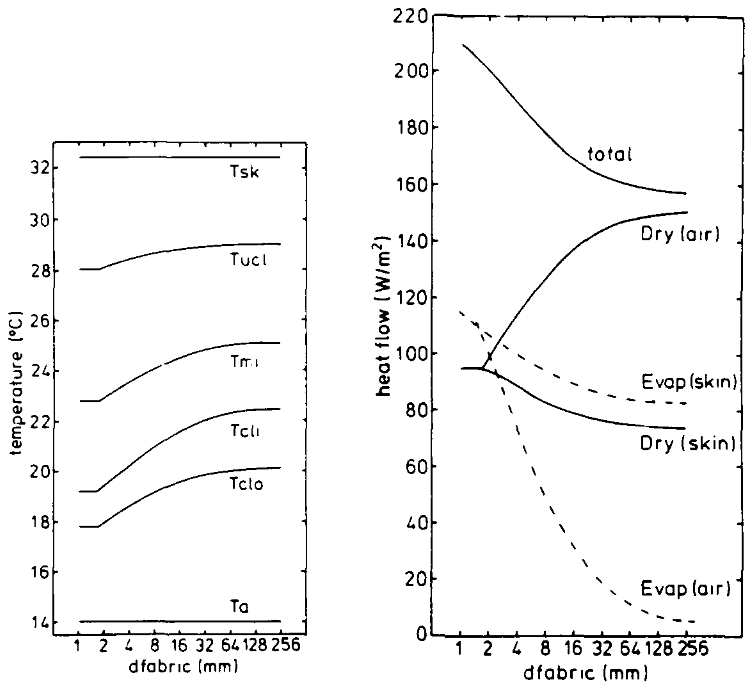

Fig. 3a (Left) Calculated temperatures of the various layers, as a function of the vapour resistance of the outer fabric.
Fig. 3b (Right) Evaporative and dry heat loss at the skin and to the air, respectively, as a function of the vapour resistance of the outer fabric. For resistances higher than about 1.7 mm condensation occurs, increasing the dry heat flow to the air at the expense of evaporative heat flow. The total heat flow decreases with increasing vapour resistance.

These predictions can be verified experimentally. In the following section three experiments are described to evaluate the model. After the experimental methods the data will be presented for the separate experiments, winding up with a comparison of calculated and experimental data.

3 EXPERIMENTAL VERIFICATION

In the first experiment (which has briefly been published in 1983: Van de Linde and Lotens, 1983) subjects walked at various temperatures with and without impermeable garments, and with and without a sweat blocking layer close to the skin. In the second experiment (Havenith and Lotens, 1984) subjects cycled at different work rates in semipermeable and impermeable garments. In the third experiment (Van de Linde, 1987) the heat strain was established during moderate and very heavy work in impermeable garments at two temperatures and with and without heat radiation.

3.1 General methods

Indirect calorimetry was used in all experiments, by determination of the heat balance equation.

$$M = Wext + Resp + Evap + Store + Dry \qquad (W)$$

where M = metabolism
Wext = external work
Resp = respiratory dry and evaporative heat flow
Evap = evaporative heat flow
Store = rate of heat storage
Dry = dry heat flow

The heat balance was taken over the last 5 to 10 minutes of 1 hr sessions and the work load and environmental conditions were chosen such that the subject would be near to thermal equilibrium and thus the Sto-term small. In the third experiment sessions were sometimes shorter and did not end in thermal equilibrium.
M was determined from O_2 consumption and CO_2 production, using Weir's (1949) formula for conversion to heat.
Wext was set to zero for treadmill walking and set to the external load during ergometer cycling.
Resp was calculated according to Fanger (1970).
Evap was either determined from continuous weight change measurements or from before and after session weighing, corrected for respiratory and metabolic weight losses. The accuracy of weighing is about 10 g.
Store was calculated from the rate of change of rectal and mean skin temperature, using weight factors of .67 and .33 respectively, in the cold and .8 and .2, respectively, in the heat.

Temperature measurements
Temperature was measured using YSI 700 series probes. The rectal probe was inserted 12 cm beyond the rectal sphincter. Skin temperatures were taken at various sites (see Table I) and area weighing was used to calculate mean temperatures. Garment inner surface temperatures were recorded with YSI thermistors, outer surface temperature with either thermistor probes, custom designed to measure in boundary layers, or with a Barnes radiative temperature meter.

Table I Locations of sensors and weighing factors used to calculate mean temperatures.

	a	b	c	d	e	f	g	h	i	j	k
Exp.1											
Tsk, rhcli	.07	.17	.1	.07		.12	.19		.20		
Tclo	.07	.17	.18	.19			.39				
Exp.2											
Tsk	.07	.17	.18	.07		.12	.19		.20		
Tcli, Tclo	.07	.12	.12	.19			.30			.08	.12
Exp.3											
front	.07	.36		.19			.39				
back			.40		.20			.40			
mean	.02	.12	.27	.06	.14		.13	.26			

a - head	d - upper arm front	g - thigh front	j - shoulder
b - chest	e - upper arm backside	h - thigh backside	k - hip
c - back	f - lower arm	i - calf	

Other measurements
Heart rate was monitored using Respironics electrodes and a custom build cardiotachometer.
Weight change of the clothing was determined using an electronic scale, accurate to 1 g.
Relative humidity underneath the clothing was measured by means of individually calibrated Philips H1 sensors, connected to custom build oscillators.
Subjective sensations were scored on the rating scales of Table II.

Table II Sensation votes for temperature and humidity.

temperature	humidity
1. very cold	1. dry
2. cold	2. damp
3. slightly cold	3. locally wet
4. neutral	4. wet everywhere
5. slightly warm	5. soaked
6. warm	
7. very warm	

Data were collected with a data acquisition system, taking samples every second and averaging those over each minute. These raw data were stored on disk for further analysis.

Statistical analysis was either carried out by means of the MANOVA and REGRESSION programs from SPSS, the MGLH program of SYSTAT, or by applying paired t-tests.

The experimental design was always balanced for order and morning/afternoon effects.

Clothing surface area was determined by planimetrical measurement of the clothing when laid flat on a table, under subtraction of overlapping areas.

Heat transfer coefficients were calculated in the usual way:

$$\text{intrinsic:} \quad hcl = \frac{Dry}{ADu\ (Tsk-Tclo)} \quad (W/m^2K)$$

$$\text{air:} \quad ha = \frac{Dry}{Acl\ (Tclo - Ta)} \quad (W/m^2K)$$

$$\text{total:} \quad ht = \frac{Dry}{ADu\ (Tsk - Ta)} \quad (W/m^2K)$$

where ADu is the DuBois skin surface area and Acl is the surface area when clothed.

3.2 Experiment 1: Impermeable garments and sweat blocking

The effect of condensation can be shown directly by comparing the heat transfer coefficient of an impermeable garment with and without sweating. The latter is achieved by wrapping the subjects in plastic foil after donning the underwear. Since the heat strain can reach unacceptable levels in this condition the environmental temperature is ad-

justed to cause approximately the same strain in all experimental conditions.

Six young healthy male subjects (height 1.77-1.83 m, weight 67-82 kg, DuBois surface area 1.93-2.05 m^2, average 1.97 m^2) walked during 1 hr sessions on a treadmill with a speed of 1.25 m/s (4.5 km/h). They were wearing either long underwear or long underwear with fatigues and an impermeable two-piece garment with hood. Both ensembles were worn with and without plastic foil. A fifth condition, with increased work rate was included. The conditions are specified in Table III. The ensembles were completed with impermeable boots and gloves, and a full face respirator.

Table III Experimental conditions of experiment 1.

condition	Ta (°C)	treadmill inclination (%)	plastic foil	clothing[1])
A	23	0	x	1
B	3	0	x	2
C	23	0		1
D	17	0		2
E	17	2		2

[1]) 1 - long underwear, rubber boots, rubber gloves, full face mask (2.03 m^2)
2 - as 1, with fatigues and impermeable rubber coated two piece garment (3.41 m^2).

The motion of the subjects can be estimated to cause an effective wind speed of .84 m/s and the air in the chamber was rather turbulent, equivalent to 1 m/s of laminar air flow. These air speeds add to an effective speed of 1.84 m/s, causing an estimated convective heat transfer coefficient for the adjacent air layer of $8.3\sqrt{1.84} = 11.3$ W/m^2K (Lotens and Havenith, 1989).

Heat balance and heat transfer coefficients

The metabolic rate when wearing the full garment was approximately 50 W higher than when wearing underwear only. Inclination of the treadmill caused another 130 W. Table IV shows how this energy production is dissipated. In the conditions with plastic foil or impermeable garment the sweat dissipation was virtually zero and has been set to zero in the heat balance. In particular in the conditions A and E there was still a considerable heat storage at the end of the session.

Dry is calculated as the remainder of the other terms in the heat balance.

Table IV Heat balance per condition (W).

condition	M	Wext	Resp	Evap	Store	Dry
A	346	0	32	0	44	270
B	421	0	54	0	15	352
C	353	0	33	140	12	204
D	403	0	40	0	7	356
E	538	34	54	0	62	388

Table V shows the temperatures at the various layers and the heat transfer coefficient calculated from the dry heat loss and the temperature gradients.
The heat transfer coefficient of the air (ha) is with 16.5 close to the expected value of 16.3, the sum of 11.3 for the convection and 5.0 for radiation.

Table V Temperatures (°C) and heat transfer coefficients (W/m^2K) per condition.

condition	Tsk	Tcli	Tclo	Ta	hcl[1]	hfabric[2]	ha[2]	ht[2]
A	34.5	-	-	21.4	27.5[3]			10.5
B	32.4	11.1	8.8	2.4	7.6	45	16.1	6.0
C	31.6	-	-	21.6	26.5[3]			10.4
D	33.9	23.6	22.0	15.9	15.2	65	17.1	10.0
E	35.1	25.4	23.8	16.8	17.4	71	16.3	10.8

[1] with reference to skin surface area
[2] with reference to clothing surface area
[3] assuming ha = 16.5.

hfabric (heat transfer coefficient of outer clothing layer) has a high value which hardly influences the total or intrinsic heat transfer coefficient. The variation is large due to the uncertainty in the small gradient over the garment.
hcl is the apparent intrinsic heat transfer coefficient as it is perceived from the outside, where the dry heat loss is observed.

Underneath the impermeable layer, however, both a dry and an evaporative heat flow exist, according to the theory. Thus the differences in hcl between the various conditions with similar clothing (B, D, and E) could be attributed to the vapour flow. In condition B, with only dry heat underneath the garment, hcl is only half that of condition D. This suggests a wet heat flow in condition D of the same magnitude as the dry heat flow. In condition E, with a higher work rate, hcl is even slightly higher, as could be expected since the excess heat will mainly be transported by excess sweat.

For the rather thin underwear of conditions A and C the plastic foil doesn't make a real difference in hcl.

The net result for the apparent total heat transfer coefficient ht is that the value for condition B is significantly lower ($p<.002$) than for the other conditions, and that there is no significant difference in heat transfer coefficient between condition A (underwear + plastic foil) and conditions D and E (underwear with fatigues and impermeable garment). This may seem incredible at first sight, but can reasonably be explained by the evaporative heat transport underneath the garment at one hand, and the unusually large clothing surface area on the other hand, which diminishes the influence of the adjacent air layer. The heat strain in condition A is even slightly higher than in D since the rate of heat storage is higher, despite the lower metabolism. This is caused by the higher air temperature.

3.3 Experiment 2: Impermeable vs semipermeable garment

If indeed condensation can compensate for lack of permeability, as far as the heat dissipation is concerned, it might be questioned that semipermeable clothing evokes less heat strain than impermeable clothing. Such results were found by Holmer and Elnäs (1984) in a 20°C environment. According to the theory the difference should become smaller, when the relative contribution of vapour transfer to heat transport increases.

We compared such garments with respect to way of heat dissipation, resulting heat strain, and discomfort in a 14°C, 90% rh environment. This environment is regarded as typical for summer rain in a temperate climate. Four young male subjects (height 1.79 - 1.90 m, weight 73-89 kg, DuBois surface area 1.82-2.17 m^2, average 2.01 m^2) cycled at 60 rpm on a bicycle ergometer, with external loads of about 60 and 105 W. They were either wearing a loose fitting polyurethane coated polyamide 2 piece rain garment (fabric vapour resistance ≈ 150 mm air equivalent) or a Gymstar semipermeable polyester microfiber garment (vapour

resistance 4.5 mm) of the same design. Underneath they were wearing short underwear and fatigues. The ensemble was completed with rubber gloves, rubber boots and a full face respirator, connected to the respiratory equipment. The clothed surface area was 2.73 m^2.

The estimated convective heat transfer coefficient of the environment is 9.6 (8,3√1,34, motion induced wind .34 m/s, turbulent air flow equivalent to 1 m/s) due to activity and turbulent air, providing an estimated ha of 9.6 + 5.0 = 14.6.

A full design of subjects, garments, and workloads was followed, comprising a total of 16 experimental sessions.

Although the design aimed for two distinct work loads in reality a distribution of metabolic rates was obtained, due to individual variance and irregularity in the setting of the external load. For that reason the metabolism was treated as a covariant, rather than as a categorical variable in the analysis.

Heat balance and heat transfer coefficients

Fig. 4 shows the heat balances of the individual sessions as a function of metabolic rate, both for the semipermeable and the impermeable ensemble.

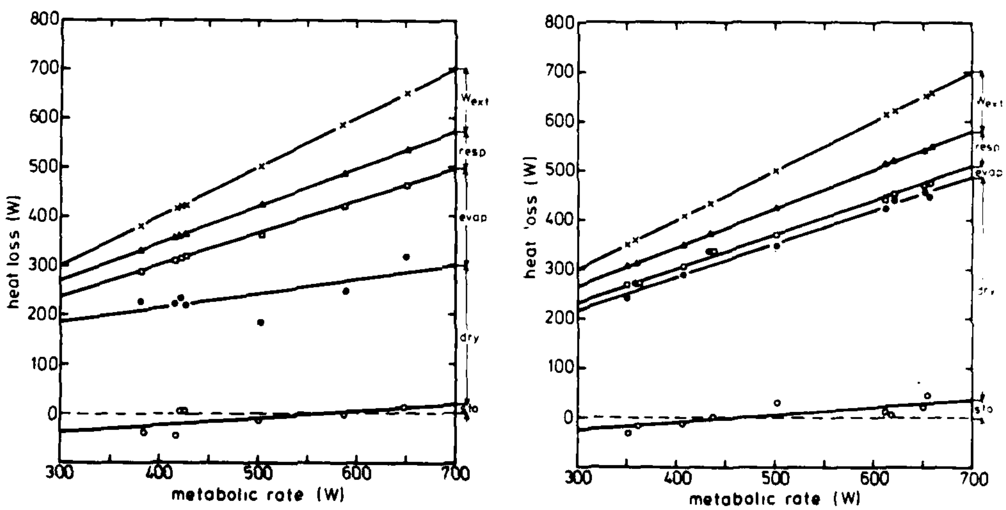

Fig. 4 The heat balance in semipermeable (left panel) and impermeable (right panel) ensembles as a function of work rate. From Havenith and Lotens (1984).

In both ensembles the storage of heat is small compared to the metabolism, showing that the produced heat is dissipated almost completely, regardless of the permeability of the garment. The way the heat is dissipated is rather different, however. With the semipermeable garment there is a considerable evaporation, whereas in the impermeable garment the evaporation is almost negligible. The difference is made up for by dry heat loss, which is much larger in the impermeable garment.

Fig. 4 shows a good linear relationship between the various terms of the heat balance and M. In order to simplify the analysis M has been standardized to M = 500 W. Table VI provides the heat exchange data, together with the statistical significance of the difference between semipermeable and impermeable ensemble.

Table VI Heat exchange data for semipermeable and impermeable ensembles, converted to equal metabolic rate of 500 W.

variable	dimension	semiperm.	imperm.	significance
Store	W	-10	5	ns
Resp	W	49	47	ns
Evap	W	128	14	p<.01
Dry	W	253	347	p<.05
Tsk	°C	32.4	33.5	ns
Tcli	°C	21.8	23.9	ns
Tclo	°C	19.6	22.6	p<.05
Ta	°C	14.0	14.0	ns
hcl[1]	W/m^2K	9.8	15.8	p<.05
hfabric[2]	W/m^2K	43	99	ns
ha[2]	W/m^2K	16.7	14.9	ns
ht[1]	W/m^2K	6.8	8.9	p<.05
Csk[3]	g/m^3	29	30	ns
Ccli	g/m^3	16.8	20.9	p<.05
Ca	g/m^3	10.9	10.3	ns
dcl[1]	mm	14.0	155	p<.01
dfabric	mm	5.4	115	p<.01
da[2]	mm	2.2	2.6	ns
dt[1]	mm	15.4	148	p<.01

[1] with reference to skin area
[2] with reference to clothing area
[3] derived from skin temperature assuming 90% wet skin.

The outside of the impermeable garment proves to be warmer than that of the semipermeable garment. At the inside this is also the case for the average value, but due to larger variance this is not statistically significant. Intrinsic heat transfer coefficient (hcl) is different, despite the nearly equal heat resistance of the ensemble components (the impermeable garment might have a higher hfabric than the semipermeable garment, but this is not significant and both are so high that their contribution to hcl is minimal). Since ha is equal for both conditions, the difference in hcl also shows in ht.

The inside of the impermeable garment has a higher water vapour concentration than the semipermeable garment. There is only a small evaporative heat flow out, however, because the vapour resistance of the fabric is much higher. The intrinsic vapour resistances (dcl) are very different as well, since the contribution of the underclothing is relatively small. Also the total vapour resistance (dt) is much higher with the impermeable garment.

All the above observations fit well into the mechanism of condensation. The higher clothing surface temperature of the impermeable garment points at a higher rate of liberation of heat of condensation, and hcl is higher because it includes the evaporative heat transport under the clothing. In itself it is no proof of condensation, however, since it could be argued that the accumulated sweat in the clothing causes direct conduction of heat. In that case the clothing temperature would steadily increase during a session, running parallel to the amount of sweat accumulated until complete soaking. Fig. 5 shows that in reality the clothing temperature rather goes along with the relative humidity of the garment's inner surface.

Although the average relative humidity is not reaching saturation, in the impermeable garment most locations are saturated, and in the semipermeable garment many. Over all tests the average relative humidity in the impermeable garment increases to 96%, and in the semipermeable garment to 87%.

Fig. 6 shows that the surface temperature of the suit increases with the metabolic rate, and the associated higher absolute skin humidity, particularly in the impermeable garment.

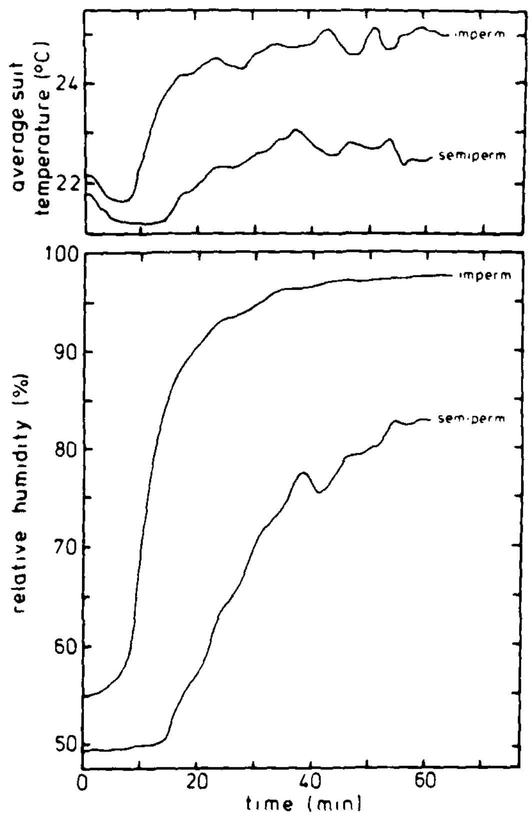

Fig. 5 Average temperature (top panel) and relative humidity (bottom panel) at the inside of the outer garment for the two ensembles. Data from one subject. From Havenith and Lotens (1984).

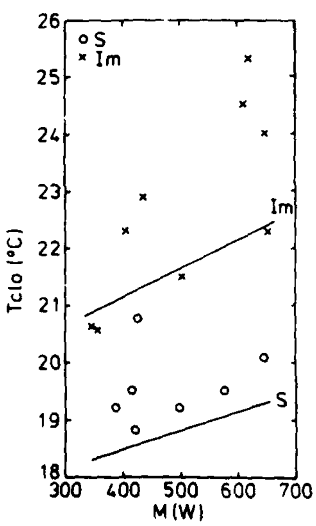

Fig. 6 Ensemble outer surface temperature as a function of workrate. Due to condensation the surface temperature increases with increasing thermal strain, and more so in the impermeable (Im) then in the semipermeable (S) garment. The drawn lines are calculated (see section 3.5).

Discomfort and strain

An interesting question is whether the equilibrium condition is reached at a higher heat load in the impermeable garment, and whether this evokes greater discomfort. Table VII shows that the heat load did not differ between the two ensembles. Tsk, sweat production, and heart rate were not significantly different and the only significant difference was found for Trect, but this difference was very small, and in favour of the impermeable garment.

Table VII Heat strain and sensations for semipermeable and impermeable garments, standardized to M = 500 W.

variable	dimension	semiperm.	imperm.	significance
Trect	°C	37.7	37.6	$p<.05$
Tsk	°C	32.4	33.5	ns
Sweat prod.(in 1 hr)	g	346	360	ns
Sweat accum.(in 1 hr)	g	169	342	$p<.01$
HR	min^{-1}	108	112	ns
temp. sensation		slightly warm/warm	warm	$p<.01$
humidity sensation		wet everywhere	wet everywhere	ns

There was a difference in sweat accumulation, and also in temperature sensation, but not in humidity sensation. In both garments the subjects felt wet everywhere and apparently increases over 170 g of accumulated sweat cannot be sensed by the subjects. Temperature sensation was slightly warmer in the impermeable garment, despite the lack of significance of the 1.1°C difference in skin temperature. Havenith and Van Middendorp (1986) showed that humidity may add to temperature sensation in warm conditions, and it is hypothesized here that the combined effect of higher skin temperature and sweat accumulation evoked the warmer sensation. This hypothesis is supported by the fact that for lower work rates the skin temperature is similar for the two ensembles, whereas both the heat sensation and the moisture accumulation became much lower in the semipermeable than in the impermeable ensemble.

3.4 Experiment 3: Impermeable garments in various environments

In this third experiment the effect of environmental temperature and workrate on heat transfer of impermeable clothing was investigated. An additional variable was heat radiation. When the surface of a garment is heated, the rate of condensation will decrease and consequently the effective heat transfer as well. Thus the effect of the radiation may be moderated by the concomitant change in heat transfer coefficient.

The experiment was dedicated to the determination of both the heat transfer and the tolerance time. In this paper only the heat transfer aspects will be addressed, however.

Six young male subjects (height 1.58-1.92 m, weight 66-74 kg, DuBois surface area 1.67-2.01 m^2, average 1.90 m^2), three of which with a good and the other three with a poor physical fitness, performed treadmill work at a speed of 1.25 m/s (4.5 km/h). The treadmill was placed in a wind tunnel, set to a frontal wind speed of 1.25 m/s. The effective wind speed is estimated to comprise of .84 m/s due to motion and 1.25 m/s due to wind, resulting in a convective heat transfer coefficient of $8.3\sqrt{2.1} = 12$ W/m^2K and a total heat transfer coefficient for the air (ha) of 17 W/m^2K.

The subjects were wearing the same ensemble as in conditions D and E of experiment 1: underwear, fatigues, dark green butyl rubber coated garment, rubber boots and gloves, and a full face respirator, with a total surface area of 3.41 m^2.

Table VIII shows the various experimental conditions. The environmental temperatures of 16 and 26 °C were combined with moderately hard and very hard work, achieved by 0 and 5% inclination of the treadmill, respectively.

Table VIII Experimental conditions of experiment 3.

condition	Ta °C	treadmill inclination (%)	radiation (W/m^2)
I	16	0	0
II	26	0	0
III	16	5	0
IV	26	5	0
V	16	0	500
VI	26	0	500

The subjects were facing a radiation panel, consisting of four quartz incandescent lamps of 1 kW each, mounted in parabolic armatures. The radiation intensity was adjusted to 500 W/m^2 at the location of the subject, illuminating the subjects right to the front.

Heat balance and heat transfer coefficient
The heat balance has been determined over the last 10 minutes of each session. Due to intolerable heat strain the work could not be sustained for a complete 1 hr session in conditions II, III, and IV, and just sustained for 1 hr in condition VI. This means that in these conditions there is still a considerable heat storage term. Table IX shows the heat balances, with Dry as the remainder.

Table IX Heat balance per condition (W).

condition	M	Wext	Resp	Store	Evap	Dry
I	348	0	40	1	25	282
II	375	0	32	89	32	222
III	659	75	75	73	46	390
IV	675	75	58	192	28	322
V	357	0	41	9	30	277/390*
VI	378	0	32	98	40	208/321*

* including absorbed radiative heat of 113 W.

In conditions V and VI the dry heat transfer has to be distinguished in the flow from the skin to the clothing, and from the clothing to the air, since radiant heat is absorbed in the garment. In contrast to the expectation, the dark green garment reflected 80% of the incident radiation, which had its peak at 1 μm wavelength. Measurement with a spectrophotometer shows that at 900 nm the reflection is even 95%. Therefore the total radiant heat amounted to just 113 W, taking into account the radiated surface area.
Table X provides the temperatures of the various layers, distinguished in front and back, since this becomes relevant for the radiant conditions. The effects of work rate and air temperature are significant ($p<.05$) on all variables and the effect of radiation only on Tcli and Tclo.

Table X Temperatures for (radiated) front and (non-radiated) back, per condition (°C). Tcli and Tclo are outer clothing layer temperatures at inner and outer face, respectively.

condition	front Tsk	front Tcli	front Tclo	back Tsk	back Tcli	back Tclo	Ta
I	32.5	21.4	19.8	32.5	22.3	20.9	16.0
II	35.9	30.8	29.1	35.8	31.0	30.0	26.0
III	34.2	24.1	21.5	34.3	24.6	22.5	16.0
IV	36.2	30.6	28.3	36.2	31.0	29.4	26.0
V	33.2	25.3	-	32.8	23.0	22.0	16.0
VI	36.3	33.9	-	36.2	31.3	30.8	26.0

Skin temperatures are equal for front and back, but without radiation the garment is systematically warmer at the back, which was observed in other experiments as well (Lotens and Pieters, 1990), both with and without wind. With radiation Tclo at the front was some 3-4°C warmer than at the back. Tclo was during radiation also systematically higher than Tcli. It was concluded that this was an artefact, due to the higher absorption of heat in the black paint of the sensors, compared to the absorption in the garment. Therefore the data for Tclo, front were discarded in conditions V and VI.

In Table XI the average temperatures and the heat transfer coefficients are given. For conditions V and VI Tclo has been estimated to be 1.2°C below Tcli like in the other conditions.

Table XI Average temperature (°C) and heat transfer coefficients (W/m^2K) per condition.

condition	average Tsk	average Tcli	average Tclo	hcl[1]	hfabric[2]	ha[2]	ht[2]
I	32.5	22.0	20.5	12.4	55	18.4	9.0
II	35.9	30.9	29.7	18.8	54	17.6	11.8
III	34.3	24.4	22.2	17.0	52	18.5	11.2
IV	36.2	30.9	29.0	23.5	50	31.0	16.6
V	33.0	23.8	22.6	14.0	-	17.4	9.7
VI	36.3	32.1	30.9	20.3	-	19.2	12.8

[1] with reference to skin surface area
[2] with reference to clothing surface area.

In the four conditions in which the temperature gradient over the impermeable garment could be determined with acceptable accuracy hfabric was quite similar, with an average value of 53 W/m^2K, as in experiment 1 for the identical garment.
hcl varies between the conditions. Linear regression shows that hcl is significantly correlated with skin temperature, but not with sweat rate or accumulated sweat in the clothing. It is thus not likely that sweat soaking of the clothing is responsible for the variance in hcl. Comparing conditions V and VI with I and II, respectively, the effect of radiation on hcl appears to be small.
The values of ha seem credible in view of the expected value of 17 W/m^2K, with the exception of the high value for condition IV. This is probably caused by the small temperature gradient between Tclo and Ta, with associated inaccuracy.

3.5 Comparison with model calculations

By means of the computer model ConRad V1.1 the total of 11 experimental conditions of the three experiments have been simulated. The model requires a number of inputs, which include environmental, skin and clothing parameters.
The actual skin temperatures and environmental conditions have been used. The humidity of the skin was supposed to be between 90 and 100%, depending on the sweat production. For the clothing the experimentally found values for hfabric, dfabric, reflection coefficient ρ, and surface area factor have been used. An estimation had to be made of the heat transfer coefficient of the underclothing hucl (underwear + fatigues), the width of the air gap, and the ventilation.
The latter is very low, due to the closed apertures and the air impermeable garments, and was set to the value of 5 l/m^2min found by Havenith et al (1990) for an impermeable coverall.
For hucl for all ensembles and conditions the value of 22 W/m^2K was used and for the trapped air 5 mm.
Table XII summarizes the main parameters, while Table XIII lists the main output, together with experimental data, as far as available.

Table XII Input values for the model simulations. hfabric is outer layer heat transfer coefficient dfabric is outer layer vapour resistance, trapped air is the width of the airgap, hucl is underclothing heat transfer coefficient, ρ is reflection coefficient for incident radiation.

exp	ensemble	hfabric (W/m^2K)	dfabric (mm)	trapped air(mm)	hucl (W/m^2K)	ρ	ventilation (l/m^2min)
1.3	all	60	250	5	22	.8	5
2	S	43	5.5	5	22	.2	5
	Im	99	115	5	22	.2	5

Table XIII Calculated and measured temperatures, vapour concentrations, condensation rates and heat flows, for the three experiments.

condition	Tucl °C	Tcli °C	Tclo °C	Ccli g/m^3	skin Evap W/m^2skin	skin Dry W/m^2skin	cond g/hm^2cloth.	air Evap W/m^2cloth.	air Dry W/m^2cloth.
S model	28.4	20.6	18.8	17.9	97	86	44	46	80
exp		21.8	19.6	16.8				47	93
Im model	29.9	22.8	21.6	20.4	108	80	148	6	125
exp		23.9	22.6	20.9				-	127
B model	24.8	9.7	8.2	3.4	0	169	0	0	94
exp		11.1	8.8					103	
D model	30.3	23.5	21.8	21.2	111	80	151	5	101
exp		23.6	22.0					104	
E model	31.5	24.8	23.0	22.8	117	79	158	6	104
exp		25.4	23.8					114	
I model	29.1	22.7	21.3	20.2	86	74	114	5	84
exp		21.4	19.8					7	83
II model	33.9	30.2	29.3	30.8	66	43	82	6	55
exp		30.8	29.1					9	65
III model	30.8	24.0	22.4	21.9	111	78	150	6	100
exp		24.1	21.5					13	114
IV model	34.3	30.8	29.8	31.7	81	41	102	7	61
exp		30.6	28.3					8	94
V model	30.8	25.1	24.0	23.2	83	67	91	5	98*
exp		25.3	(24.1)					9	114*
VI model	35.2	32.4	31.8	34.4	62	37	49	7	68*
exp		33.9	(32.7)					12	94*

* includes radiative heat

The first four data columns deal with temperature and humidity, the last five with heat flows and rate of condensation. It can be observed that underneath the outer garment Evap is usually larger than Dry (with exception of condition B of course), whereas at the outside of the garment Dry exceeds Evap by far. This is associated with a rate of condensation that runs up to 540 g/h for condition E. It should be noted that the heat flows from clothing to air do not add up to the same value as at the skin since the clothing surface area is larger than that of the skin. Multiplying by the actual surface area gives the total heat flow in W and this matches between skin and clothing.
In Fig. 7a a comparison is made between the measured and calculated clothing temperature. There is a close agreement, even for the radiation conditions V and VI.

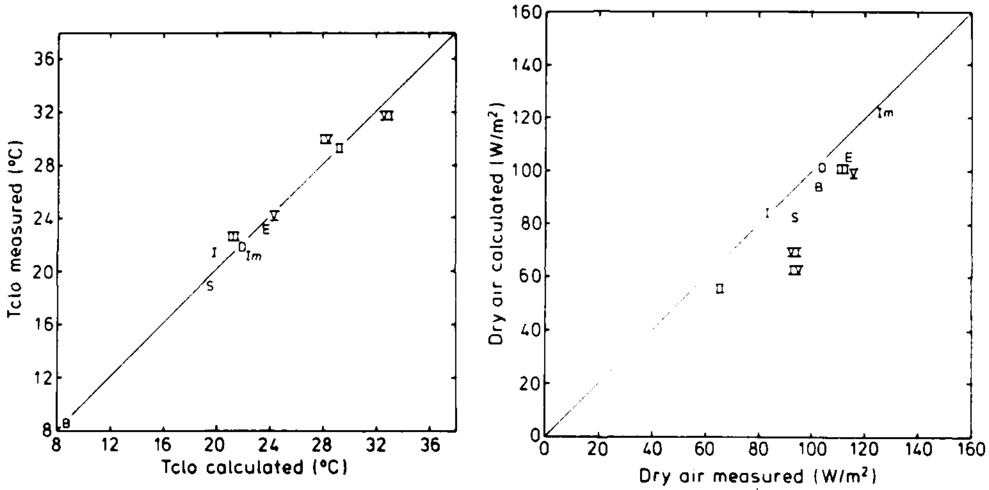

Fig. 7 Measured versus calculated garment outer surface temperature (a) and dry heat loss to the air (b) for the various conditions in the three experiments.

When the same correlation is plotted for the dry heat loss to the air (Fig. 7b) also a good agreement is obtained, but less so for conditions IV and VI. For condition VI the calculations give a Tclo for the shadow side of 1.3°C lower than measured. This would make up for 18 W/m^2, the main part of the observed discrepancy between measured and calculated dry heat loss. For condition IV there might be experimental inaccuracy involved since in this condition the subjects were storing heat at a high rate, which not only decreases the magnitude of Dry, but also introduces additional uncertainty.

Fig. 8 shows hcl (the heat transfer coefficient of the clothing assembly as calculated from the apparent dry heat loss to the air and the temperature gradient from skin to clothing. Note that this dry heat loss (Dry) is calculated from the heat balance equation and thus includes wet heat transfer under the clothing, but not absorbed heat due to radiation). There is a reasonable agreement between measurement and calculation.

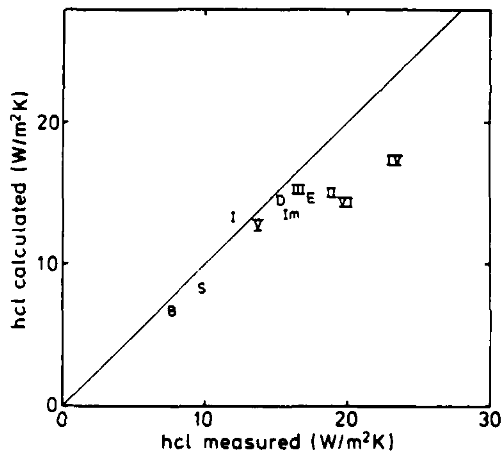

Fig. 8 Measured versus calculated apparent heat transfer coefficient for the various conditions in the three experiments.

The accuracy for the radiant conditions and condition IV is less than for the other conditions due to the explained reasons. Overall, the condensation mechanism seems to account completely for the more than a factor of 3 variance in the observed hcl for the same ensemble in various conditions.

In Fig. 6, the garment surface temperatures were given for the individual sessions in the Im and S ensembles, as a function of M. Increasing metabolism is associated with increasing skin temperatures and skin humidities. When these are put in the model the two lines in Fig. 6 are obtained, for the two ensembles, respectively. The calculated temperatures came close to measured values and show the experimentally found increase with M. For a fixed skin humidity the lines would only reflect the effect of skin temperature and would run a bit less steep and parallel to each other.

4 DISCUSSION

Condensation mechanism

The condensation mechanism accounts for a number of phenomena, not only in a qualitative, but also in a quantitative way. The coincidence of rise in relative humidity and temperature at the inside of the outer garment (Fig. 5) is very suggestive and in particular the observed higher surface temperature of impermeable clothing compared to semipermeable wear, and the dramatic changes in apparent intrinsic clothing heat transfer coefficient are satisfactorily explained. As such no other explanations are required. It could be argued, however, that the wetness of the underclothing causes some additional conduction and therefore may contribute to the same phenomena. It is unlikely that the actual cotton underclothing and fatigues, with an absorption capacity of 30 g water vapour per 100 g of dry fabric before any free water is created, will show such conduction when the total absorbed mass is less than 200 g. But already early in the experimental sessions when little moisture is accumulated, the typical effects show that should be absent with conduction only. Moreover, it was concluded in section 3.4 that there was no correlation between hcl and sweat accumulation. Since the condensation mechanism has to be accepted as the better explanation in conditions with moderate sweat accumulation, and since this same mechanism is a *sufficient* explanation for conditions with profuse sweat, it is concluded that conductance had no relevant effect in the experiments described here.

Parameter values

The quantitative fit between experiment and theory depends on a number of parameters in the model. Most parameters are known clothing properties (surface area, fabric vapour resistance, reflection coefficient for radiation), environmental conditions (effective wind, air temperature and humidity, radiation intensity), or skin conditions (skin temperature).

Other parameters can safely be estimated (ventilation). Uncertainty concerns the heat transfer coefficient of the underclothing, the width of the trapped air layer, and the relative humidity at the skin. It has been assumed that hucl is 22 W/m^2K, gap width is 5 mm, and that the relative humidity at the skin varies from 85 to 100%, depending on the sweat rate. Sweat rates start at 350 g/h and run up to over 1 l/h.

Worn without an overgarment the underclothing (underwear + fatigues) would have typically an insulation of .8 clo, equivalent to hcl = 8 W/m^2K. Due to motion in free air this would increase to 15 W/m^2K (Lotens and Havenith, 1989b). It is not unlikely that due to compres-

sion by the outer garment and due to enhanced internal convection under the outer garment this value increases with some 50% to 22 W/m^2K. The gap width is a rough estimate. This parameter is not very critical, however, still the internal convection due to pumping and ventilation always evokes a high heat transfer coefficient.
The skin humidity has not been measured, but observations on the subjects showed that their skin was wet over the entire surface in most conditions, which is to be expected from the observed moisture accumulated in the clothing and the sweat rate. Moreover, the calculations show that in the simulation of experiment 2, with impermeable and semipermeable clothing the measured values of Tcli, Tclo, and Cclo are correctly predicted, given the assumption of skin wetness.
It can be concluded that there were few degrees of freedom to make the model fit to the data. Estimated parameters have been kept at the chosen value for all garments and conditions.

Sensitivity analysis

The model lends itself well to investigate the importance of the parameters involved. To that purpose all parameters have been systematically changed over a realistic range of values to see the effect on Tclo, Dry, hcl, dcl, and total heat flow (HF).
Condition I (exp. 3) has been taken as a reference. The results are compiled in Table XIV.

Table XIV Changes in calculated variables induced by modified parameters for the impermeable ensemble. In the last column the changes in the difference between the total heat flow from semipermeable and impermeable ensembles are given, as modified by the listed parameters.

	impermeable ensemble					semipermeable vs imperm. ensemble
	Tclo	Drya	hcl	dcl	HF	HF
more ventilation	□	□	□	++	++	□
higher insulation	+	-	-	□	-	-
lower surface area	□	+	□	□	□	+
dry skin	++	--	--	□	--	-
cool envir.	--	++	□	□	++	□) -
warm envir.	++	--	□	□	--	□) +
high skin temp	+	+	□	□	+	□
no wind	++	-	□	□	-	□
additional radiation	++	+	□	□	+	□

-- much lower - lower □ small changes + higher ++ much higher

Obviously Ta, radiation, and to a lesser degree Tsk, have a strong effect on Tclo. Of the other parameters, skin humidity and wind have a strong effect and insulation (gap width, thickness of the underclothing, and thickness of the outer fabric) a moderate effect. Ventilation and clothing surface area are not so relevant.

For Drya skin humidity is as strong a parameter as Ta: dry skin compensates a 10°C drop in environmental temperature. Wind and radiation are less important for Drya than suspected from their effect on Tclo, and comparable to the effect of insulation. Ventilation has virtually no effect on Drya.

As a result of Tclo and Drya, hcl is most influenced by skin humidity. Insulation has a smaller effect, and ventilation, clothing surface area, cold, heat, wind, and Tsk few or none. This analysis confirms the wide variation in hcl found between conditions B and IV and shows that the uncertainty in other parameters than skin humidity and radiation plays a minor role. Dcl is strongly affected by ventilation and hardly by all other parameters. This is clear from the fact that neither addition of resistance, nor changes in driving force will affect the high value of dcl. Ventilation, however, is a parallel way to dissipate vapour and is a strong competition to the vapour transfer through the clothing material.

Total heat flow (HF) depends on Ta, but certainly as strong on ventilation, exclusively via Evapa, and on skin humidity. Insulation, radiation, surface area, and wind speed have a smaller effect.

The effect of increased permeability of the outer garment has been investigated in more detail. Permeability has of course a very strong effect on dcl, but also a strong effect on Drya and hcl, and a considerable effect on Cclo and Tclo.

Total heat loss in the reference condition is considerably improved by permeability. It increases from 97 to 137 W/m^2 when dfabric drops to 2 mm. This effect is modulated by interaction with other parameters. (Table XIV, last column). The difference of 40 W/m^2 becomes larger in the heat and with higher skin temperature, and progressively larger with high skin temperature in the heat. In the cold it decreases, and also with dry skin or higher insulation of the underclothing.

There is hardly an interaction between permeability and ventilation, wind speed or radiation. The effect of permeability is enhanced by tight fit, but this is mainly due to the fact that heat loss is expressed with reference to clothing surface area. The actual difference in heat loss over the body (in W) is just slightly increased by tight fit.

Radiation

In experiment 3 the physiological strain in condition V was completely similar to that in I, and VI to in V. The difference in conditions is the external radiation and it is an at first sight unbelievable fact that 500 W/m^2 of external radiation has no effect at all on the heat strain.

Much is explained by the reflection coefficient of the rubber coated garment, that was close to unity in the 900 nm region, despite the dark green colour in the visual range. The garment thus absorbs only 20% of the energy in the spectrum of the source.

The heat that is nevertheless absorbed increases the surface temperature with some 2.5 °C, decreasing the heat loss at the radiated side. However, it is hypothesized that the consequently higher concentrated vapour is transferred by internal convection to the non-radiated side, causing there increased condensation and an increased surface temperature. Indeed this temperature is 1°C higher in radiation conditions, and thus enables the dissipation of some extra heat. The model shows that even without this mechanism the heat flows leaving the skin are only marginally lower in radiation conditions (10 W/m^2) and thus justify the lack of difference in heat strain.

Discomfort

Table VII showed that there was no marked difference in heat strain caused by semipermeable vs impermeable ensembles. The only difference was that the impermeable ensemble collected more sweat. This was not apparent in the humidity sensation ("wet is wet"), but the wetter garment gave a slightly warmer sensation. The model predicts virtually equal total heat flow leaving the skin for the two ensembles. Apparently the condensation mechanism was able to compensate fully for the lack of latent heat transfer and the wearer became wet in both ensembles. Studies by Gilling et al. (1977) and Light et al. (1987) confirm that there is no difference in heat strain between permeable and impermeable garments for subjects who work in the cold, but a significant difference in the heat. In Gilling et al's study subjects worked at 490 W for 60 min and rested for 30 min in 0°C. They heated up very similarly but cooled down slightly slower in the impermeable garment. Moisture accumulation was significantly higher in the impermeable garments, but subjectively rated as only slightly wetter. Light et al.'s subjects sat for 90 min in 21 and 30°C air temperature. Skin temperature was higher in the impermeable garment at 30°C only and moisture accumulation at both temperatures, but more at 30°C. Comfort votes were not different at both temperatures.

The real advantage of semipermeable wear in the cold is that the clothing will dry during periods of inactivity. This provides more comfort in the long run, as has been confirmed by various practical tests (van de Linde e.a. 1989, Gilling e.a. 1977).

Comparison with other studies

There are not so many sufficiently documented studies on impermeable clothing in the literature. Most studies deal with resulting heat strain in specific conditions, but don't allow a numerical check on heat transfer. An exception is the study of Holmer and Elnäs (1981) on a comparison between three ensembles: an overall, covered with an impermeable or semipermeable two piece overgarment, or without overgarment. They measured the humidity at the skin, but no data are available on humidity and temperatures at the garment's surface. Thus only the total dry and wet heat loss can be compared with a model calculation. The vapour resistances of their garments were not specified but it can with sufficient accuracy be estimated that the impermeable overgarment had a dfabric of 250 mm and the semipermeable Goretex overgarment of 2 mm (Farnworth et al., 1990). An important aspect of their experimental procedure is that face and hands were uncovered and sleeves, neck and trousers not closely tightened. The model shows that this has a strong impact on total heat transfer and actually obscures the real difference between the garments. It is estimated that the resulting ventilation amounts to 50 $l/m^2 min$, which is the value we found under comparable conditions, using a tracer gas technique (Lotens and Havenith, 1988). Table XV shows the measured and calculated data, both with and without ventilation and uncovered skin.

Table XV Comparison between measured and calculated heat flow (W/m^2 skin area) for the study of Holmer and Elnäs (1981).

	semipermeable		impermeable	
	Evapa	Drya	Evapa	Drya
experimental	75	78	49	111
model	91	66	45	94
model (without ventilation, skin covered)	53	75	17	75

In contrast to the convention followed in this paper the heat flows to the air have been recalculated per unit of skin area, to make them comparable to the measured data. The table shows that ventilation and bare skin have a dramatic influence on Evapa. The table also shows that with ventilation there is reasonable concert between measurement and calculation, but this is obviously troubled with uncertainties. An indirect proof of ventilation is the only 54% skin humidity that was measured in the impermeable garment, despite the 175 g of moisture accumulation in the clothing. Without ventilation this skin humidity would be unlikely. The model indicates that in no condition there would be condensation and that thus the heat strain in the impermeable garment should be the largest, since compensation by the condensation mechanism for the lack of permeability does not take place. Indeed Tsk, Tr, and skin humidity are higher in this garment, although only the latter is clearly significant.

5 CONCLUSIONS

Sweating in clothing with low vapour permeability may play a major role in heat dissipation. Sweat is evaporated at the skin and condensates at the low permeable layer, thereby carrying heat. This mechanism is able to compensate fully for the lack of vapour (and latent heat) dissipation to the environment. Thus in cool conditions with wet skin there is hardly any difference in heat strain between permeable and impermeable garments. With dryer skin, or in the heat, when condensation is prevented, impermeable garments allow less heat transport. A numerical model, calculating heat exchange and temperatures in the various layers in the clothing ensemble gives an adequate quantitative description.

In actual wear in cool environments the difference in comfort between permeable and impermeable garments is only manifest during prolonged wear. During heavy work subjects are rating equal wetness but during periods of inactivity semipermeable garments allow drying of the underclothing.

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Soesterberg, April 2, 1990

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APPENDIX <u>Equations in the model and solution method</u>

Referring to Fig. 1 the following expressions for the resistances are used

A = 1/hucl

B = 1/hinter = $1/8.3\sqrt{32 \text{ Vent/gap}}$ fucl

C = B fucl/fcl

$$D = \frac{(1-\rho ucl\ \rho cl)(Tucl - Tcli)}{fucl\ \varepsilon ucl\ \varepsilon cl\ \sigma\ (Tucl^4 - Tcli^4)}$$

$$E = \frac{Tucl - Ta}{fucl\ \varepsilon ucl\ \varepsilon cl\ \sigma\ (Tucl^4 - Ta^4)}$$

F = 1/rho Cp Vent fcl

G = 1/hfabric fcl

$$H = 1/fcl\ hr = \frac{Tclo - Ta}{fcl\ \ \varepsilon cl\ \ \sigma\ (Tclo^4 - Ta^4)}$$

I = 1/hc fcl=$1/8.3\sqrt{V}$ fcl (Kerslake, 1972)

J = ducl = 1.3 * thickness + .001 (m) (Lotens and Havenith, 1989b)

K = λa/hinter

L = K fucl/fcl

M = 𝔻/Vent fcl

N = λa/hc fcl

O = dfabric/fcl

where Vent = ventilation in m^3/m^2s = m/s
fucl = underclothing area factor
gap = trapped air layer width (m)
Temperatures are in K

ρ = reflection coefficient
ε = absorption coefficient
τ = transmission coefficient
σ = Stephan Bolzmann constant = 5.67 10^{-8} (W/m^2K^4)
rho = density of air (kg/m^3)
Cp = heat capacity of air (J/kgK)
V = effective wind velocity = sum of velocities induced by natural convection, wind, and activity (Lotens and Havenith, 1989b)
λa = heat conductivity of air = .026 (W/mK)
𝔻 = diffusion constant for water vapour in air = 25.10^{-6} (m^2/s)

Again referring to Fig. 1, the equations to be solved follow from the law of conservation of energy at star prints, and the fact that the gradient over a closed loop must equal zero thus follows that for the heat network:

$$hfA - hfB - hfD - hfE = 0 \quad (1)$$
$$hfB - hfF - hfC = 0 \quad (2)$$
$$hfC + hfD + hfcondensation - hfG = 0 \quad (3)$$
$$hfG + hfradiation - hfH - hfI = 0 \quad (4)$$
$$B\ hfB + C\ hfC - D\ hfD = 0 \quad (5)$$
$$C\ hfC + G\ hfG + H\ hfH - F\ hfF = 0 \quad (6)$$
$$B\ hfB + F\ hfF - E\ hfE = 0 \quad (7)$$
$$A\ hfA + E\ hfE - Tsk + Ta = 0 \quad (8)$$

and for the vapour network:

$$vfK - vfM - vfL = 0 \quad (9)$$
$$vfL - vfcondensation - vfO = 0 \quad (10)$$
$$vfS - vfK = 0 \quad (11)$$
$$vfO - vfN = 0 \quad (12)$$
$$L\ vfL + O\ vfO + N\ vfN - M\ vfM = 0 \quad (13)$$
$$J\ vfJ + K\ vfK + M\ vfM - Csk + Ca = 0 \quad (14)$$

where hf = heat flow and vf = vapour flow.
Both sets of equations can separately be solved, but one unknown variable remains: the rate of condensation. Both solutions should accommodate either the conditions that the rate of condensation is zero, so that the solutions are independent or that the rate of condensation is such that Ccli = Cmax(Tcli), where Cmax is the vapour saturation function.
This procedure is carried out by the program ConRad V1.1, providing accurate solutions in an iterative way. The sets of equations are solved by matrix manipulation. First the heat and vapour flows are solved and then the temperatures and vapour concentrations are calculated using

$$T = T' + R'.hf \quad (°C)$$

$$C = C' + \frac{d'.vf}{D} \quad (g/m^3)$$

where R' and d' are the heat and vapour resistances between T and T', and between C and C', respectively.

REPORT DOCUMENTATION PAGE

1. DEFENCE REPORT NUMBER (MOD-NL) TD 90-0033	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER IZF 1990 B-5
4. PROJECT/TASK/WORK UNIT NO. 736.1	5. CONTRACT NUMBER B87-63	6. REPORT DATE April 2, 1990
7. NUMBER OF PAGES 40	8. NUMBER OF REFERENCES 19	9. TYPE OF REPORT AND DATES COVERED Final

10. TITLE AND SUBTITLE

The effect of condensation in clothing on heat transfer

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14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

A condensation theory is presented, that enables the calculation of the rate of vapour transfer with its associated effects on temperature and total heat transfer, inside a clothing ensemble consisting of underclothing, enclosed air, and outer garment. The model is experimentally tested by three experiments: 1 impermeable garments worn by subjects with and without plastic foil around the skin, blocking sweat evaporation underneath the clothing; 2 comparison of heat loss in impermeable and semipermeable garments and the associated discomfort and strain; 3. subjects working in impermeable garments in cool and warm environments at two work rates, with and without external radiation, until tolerance.
The measured heat exchange and temperatures are calculated with satisfying accuracy by the model,(mean error = 11, sd = 10 W/m^2 for heat flows and .3 and .9 °C for temperatures, respectively). A numerical analysis shows that for total heat loss the major determinants are vapour permeability of the outer garment, skin vapour concentration, air temperature and clothing insulation. In the cold the condensation mechanism may completely compensate for the lack of permeability of the clothing as far as heat dissipation is concerned, but in the heat impermeable clothing is more stressful.

16. DESCRIPTORS Clothing Physiology Effects of Heat Effects of Humidity Mathematical Models	IDENTIFIERS Condensation Impermeable Clothing

17a. SECURITY CLASSIFICATION (OF REPORT) -	17b. SECURITY CLASSIFICATION (OF PAGE) -	17c. SECURITY CLASSIFICATION (OF ABSTRACT) -
18. DISTRIBUTION/AVAILABILITY STATEMENT Unlimited availability		17d. SECURITY CLASSIFICATION (OF TITLES) -

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2. Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie

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Plv. Hoofd Wetenschappelijk Onderzoek KL

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6. { Hoofd Wetenschappelijk Onderzoek KM
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